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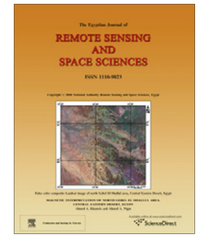

Monitoring some environmental impacts of oil industry on coastal zone using different remotely sensed data

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Coastal zone

Abstract This research paper is concerned with the impact of oil exploration and production activities on the physical and environment parameters of a coastal zone. Such impacts are the main environmental stress that led to the deterioration of the overall environment of the area under investigation. Different remotely sensed data were used in an integrated way for conducting this research. The remotely sensed data include images from landsat enhanced thematic mapper (ETM+), shuttle radar topography mission (SRTM), and data from ground geo-electrical investigation.

Sequential landsat satellite images were used to identify changes that occurred in the land-cover and land-use classes including changes in water bodies, sabkhas, vegetation cover and areas of crude oil leakage as a point contamination source. SRTM data was used to build a digital elevation model (DEM) and to study some terrain characteristics of the area, including surface topographic features and surface water and contamination regime. Based on the findings of a geo-electric survey using Schlumberger geo-electric sounding, the ground water level was measured and the presence of fresh, brackish or salt water was identified. A field investigation was conducted and the surface and ground water contaminations were monitored and measured. A geographic information system (GIS) was applied to include all these data layers as an active database for the area for the purpose of identifying hot spots and prioritizing locations based on their environmental conditions as well as for monitoring plans.

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Various environmental parameters which might be affected by pollution resulting from activities related to the oil industry were identified and hot spots that might be subjected to environmental deterioration were pointed out for immediate measures for environmental protection.

1. Introduction

The coastal area of Ras Ghareb is located in the north Eastern Desert, Egypt, on the western coast of the Gulf of Suez. It is located between latitudes 27° 45′ and 28° 45′ N and longitudes 32° 00′ and 33° 30′ E. The main town in the area is Ras Ghareb which represents a purely oil exploration, production and export town, with a population of about 60,000. The area can be reached by the coastal road extending from Suez to Halaib, where Ras Ghareb is located at 184 km south of Suez, and it is connected to the other towns on the Red Sea coast by the coastal main road (Fig. 1). Also, there are two new roads crossing the north Eastern Desert; one extends from Kattamiya, east of Cairo, to Ain Sukhna, and the other connects Sheikh Fadl in the Nile Valley to Ras Ghareb. Since the big discovery of the first commercial oil field in Ras Ghareb in 1938, oil resources provide an important foundation for life and development in the area. With increasing oil fields, the area became one of the important oil producing provinces along the western coast of the Gulf of Suez. The study area includes six large oil fields (Table 1) and there are several others in its vicinity to the north and south. Furthermore, in the nearby mountainous range to the west, there are several occurrences of industrial minerals and rocks such as kaolin, glass sand, quartz, feldspar, marble and other ornamental stones, as well as raw materials that can be used in building and construction industries.

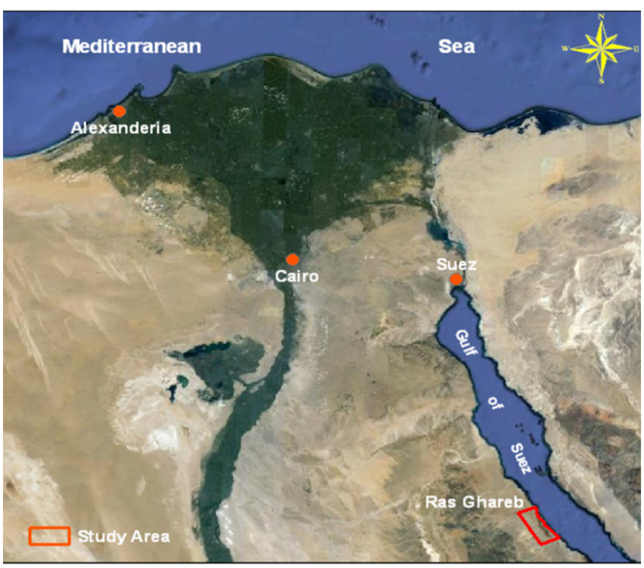

Figure 1 Location map of the study area.

Water is considered the chief environmental problem in the study area, where fresh water is a critical resource. The surface water provided by run-off after the scarce rainfall, is potable fresh water but limited in quantity and non-existent in rainless years. During the occasional winter rains, run-off from the mountains may result in some flash floods that reach as far as the coast of the Gulf of Suez, causing some damage in roads and constructions. On the other hand, wadi floods make their chief contribution in recharging the groundwater aquifer system In the sandy floor of the wadis, water can be reached at depths of around 10 m, but in the fringes of coastal flats and sabkhas, the groundwater is usually brackish not suitable for human consumption, but some of it is drinkable for camels. Currently, the supply of fresh water is based mainly on groundwater aquifer and desalination of sea water, where there are small salt marshes at Ras Ghareb. With the increasing activities in oil industry and the consequent development projects in this area, there is an environmental threat of oil pollution to soil and groundwater as well as to the coastal and marine ecosystem. Most of the productivity of natural living systems is confined to the coastal strip, which is the area associated with human activities and environmental pressure.

The waste water from oil exploration and production activities is usually brine, contaminated with petroleum hydrocarbons and heavy metals. Leaks, spills and discharge of this water in land may contaminate both soil and groundwater. Meanwhile, disposal of these untreated waste water and drilling mud to the sea could harm the marine ecosystem. According to Frihy (2001), rapid and uncontrolled coastal development, together with improperly designed projects, has had a damaging impact on the Egyptian coastal ecosystem. He made an evaluation to 13 selected projects pertaining to their negative environmental reactions on the coastal zone of the Mediterranean Sea. These projects involve harbors/marinas,

Table 1 Oil fields in ras ghareb area (After EGPC, 1996).

S. No.	Field name	Date of discovery	Coordinates		Remarks
			Latit., N	Longit., E	
1	Ras Ghareb	1938	28° 21′ 21″	33° 05′ 57″	225 km SE of Suez
2	Um El-Yusr	1967	28° 20′ 53″	33° 13′ 54″	15 km SW of Ras Ghareb
3	Kareem	1958	28° 12′ 46″	33° 02′ 29″	17 km S of Ras Ghareb
4	Shukeir	1966	28° 05′ 56″	33° 13′ 26″	30 km SE of Ras Ghareb
5	Kheir	1972	28° 09′ 14″	33° 10′ 45″	35 km SE of Ras Ghareb
6	Al-Ayun	1968	28° 14′ 30″	33° 03′ 59″	16 km SW of Ras Ghareb

recreational centers, protective structures, estuaries and lagoon inlets.

Accordingly, it is vital to identify the hot spots that are or could be subjected to environmental deterioration, in order to carry out the appropriate protective or remedial actions and measures. In this work, different remote sensing data from Earth-observation satellites and ground geophysical survey, field studies and laboratory analyses are applied in an integrated way to delineate areas subjected to different natural and man-made stresses in the Ras Ghareb area.

2. Materials and methodology

2.1. Satellite imagery data

Satellite images, with high spatial and spectral resolution, were acquired, processed and interpreted to produce baseline maps for the physical environment of the study area. For this purpose, two different types of satellite data were used to identify the geomorphic features in the area, particularly the drainage basins and flood routes that affect the general ecology and cause some environmental stress and deterioration.

2.1.1. Landsat thematic mapper (TM) and enhanced thematic mapper (ETM+) data

Two Landsat images covering the study area (Path 175/Row 040), acquired in 1984 and 2000, were used in this work to detect the environmental change that happened to the area in 16 years.

The raw satellite data were geometrically rectified and radiometrically balanced before image processing using ERDAS Imagine software version 9.2. The image processing technique applied is mainly false-color composition of the spectral bands 2, 4, 7 rendered in red, green, and blue (R–G–B) (Lillesand and Kiefer, 2000). The data of both Landsat images were georeferenced and reformatted to a GIS environment using UTM system, Zone 36 N and datum WGS-84.

2.1.2. Shuttle radar topography mission (SRTM) data

The SRTM is a specially modified Interferometric synthetic aperture radar (In-SAR) system that was flown onboard the space shuttle "Endeavour" during its eleven-day mission in February 2000. During this mission, SRTM gathered elevation data, with a resolution of 3 arc. second (~90 m), on a near-global scale to generate the most complete high-resolution digital topographic database of the Earth's surface (USGS, 2005). The raw data of SRTM covering the study area have been corrected and processed to produce a digital elevation model (DEM), which is useful in studying the geomorphic features in the concerned terrains. Digital analysis of this DEM could produce various thematic maps for contours, elevation zones, slope, aspect, and drainage network and basins, which would be used as layers for GIS (Hegazy and Effat, 2007).

The satellite data were analyzed, screened and interpreted using information from field work, topographic maps of scale 1:50,000 (Survey Department, 1995) and geologic map of scale 1:500,000 (EGPC/CONOCO-Coral, 1987). The previously mentioned paper maps were scanned, rectified by using ERDAS Imagine software version 9.2 (Leica Geosystems, 2008) followed by on-screen digitizing by using Arc/GIS platform to build a digital database and extract useful parameters (ESRI, 2006).

2.2. Ground geophysical survey

The geophysical survey applied in the study area comprised electrical exploration of the geological and hydrological features in the area. The survey dealt with the electrical state of the earth and provided conclusions concerning the electrical properties of rock formation, particularly resistively, under different geological environments. So, the electrical resistively method was carried out using Schlumberger configuration (vertical electric sounding) to detect the subsurface geology and to determine the thickness of the different lithologic layers through the subsurface section.

In this method, an electric current (a direct current or very low frequency alternating current) is introduced into the ground by two or more electrodes, and the potential difference is measured between two points (probes) suitably chosen with respect to the current electrodes. The potential difference for a unit current sent through the ground is a measure of the electrical resistance of the ground between the probes (Bhattachary and Patra, 1968).

2.3. Water and soil sampling and analyses

During the field work for ground-truth information and checking the interpretation of satellite and geophysical data, samples from surface water bodies, groundwater wells and soil profiles were collected and their locations were accurately determined using a portable GPS. These samples were subjected to chemical analysis in order to detect and identify any crude oil components contamination.

2.3.1. Surface water samples

Six locations were identified in the surface water bodies and salt marshes in the study area, where samples were collected for laboratory analysis. This aims at acquiring quantitative characterization of the surface water quality and to assess the impacts of oil exploration activities. The collected six samples were analyzed for the following chemical parameters; COD, TDS, TKN, oil and grease, H_2S, heavy metals, TOC and BTEX.

2.3.2. Groundwater samples

Groundwater level and flow characteristics were assessed by the geophysical survey. According to the drainage basins in the study area, slopes and aspect, 15 groundwater monitoring wells were already drilled. In the present study groundwater samples were collected from these wells to detect the fate of spills resulting from the various activities at the oil fields in the study area.

2.3.3. Soil samples

Four boreholes were drilled throughout the area for measuring the depth of soil impacted by oil leakage from storage tanks. Soil samples are taken from these boreholes and from other trial bits excavated in four other locations to collect shallow soil samples.

3. Climatic conditions

Knowledge of the climatic conditions is important to such a study, since they determine or affect the rainfall that represents

Table 2 Monthly average of some climatic elements measured at Suez Marine Meteorological Station during 1987–1996 (After Egyptian Meteorological Authority, 1996).

Month	Air temperature, °C			Relative humidity, %	Rainfall, mm	Sunshine, %
	Max.	Min.	Mean			
January	22.2	8.5	15.3	56–69	0.1–22.8	65–70
February	22.8	8.9	15.8	55–64	0.2–11.7	70–75
March	25.7	11.7	18.7	50–62	0.2–17.4	70–75
April	30.9	14.3	22.6	41–53	0.1–1.1	70–75
May	34.8	18.6	26.7	41–50	0.0–0.3	80–85
June	39	21.3	30.2	44–53	0.0–1.9	80–85
July	38.5	23.1	30.8	49–58	0	80–85
August	39	22.5	30.7	52–61	0	80–85
September	37.5	21	29.2	53–61	0.0–0.5	80–85
October	34.3	18.7	26.2	57–61	0.0–8.1	80–85
November	29.1	12.7	20.9	56–66	0.0–6.7	75–80
December	24.3	10.2	17.2	59–68	0.2–14.2	65–70
Annual mean	39	8.5	23.7	41–69	15.0–22.8	70–75

a critical resource for fresh water or it may cause torrential flash floods. The terrestrial and marine climate influences many physical features which cause some impacts on the environment. Generally, the climate of the study area is semi-arid, characterized by hot dry summers, moderate winters and very little rainfall. The main characteristics of some climatic elements (Table 2) are briefly discussed in the following (Meteorological Authority, 1996).

3.1. Air temperature

It ranges between 10 °C and 15 °C in winter and between 25 °C and 30 °C in summer, with an average yearly value around 22 °C. However, in some years the air temperature may exceed 36 °C in some summer days.

3.2. Relative humidity

The average relative humidity in the study area is generally moderate, ranging between 50% and 60% for most of year, except during parts of the winter season where it reaches about 70% in the months of November–February, particularly along the coast. On the other hand, westward inland, the relative humidity decreases to 30% or even less in the months of May and June.

3.3. Wind

The wind regimes in the study area have an annual average of 8–10 m/s throughout the year; the wind direction is generally NNW except for the occasional southerly winds that blow during winter. The effective prevailing wind direction is generally from the north and/or northwest for over 57% of the year. During the period from October to May, the prevailing wind comes from the northwest whereas it comes from the north during the rest of the year. Wind speed ranges from one to 27 Knots. The wind may generally be considered calm except for the Khamaseen wind which is seasonal and occurs in April. This Khamaseen wind comes from south with a speed exceeding 28 Knots; however, it does not last for long periods.

3.4. Rainfall

Rainfall over the study area and its environs as a whole is very limited, scarce and sparse, where it occurs intermittently and it is often localized, and it happens at an average of 11 days only per year. Sometimes, the area receives rainfall of about 25 mm/year only during four months (November–February) while the other months have almost no rain. Statistically, there are periodic cycles from 5 to 10 years at which rainfall may exceed 50 mm per day causing flash floods in the area.

3.5. Sun shine

The average monthly percent of sunshine hours ranges from 65% to 70% in winter months to 80–85% in summer months. Accordingly, the study area enjoys a rather high solar radiation intensity ranging from 1.900 to 2.600 $Wh/m^2/year$. Meanwhile, the annual evaporation reaches 300 mm, and the maximum evaporation rate occurs in June and July.

4. Geomorphology

4.1. Regional geomorphology

Ras Ghareb area comprises various geomorphological features resulting from different types of endogenic and exogenic processes. Generally, it can be subdivided into three main geomorphologic units, namely from west to east: mountainous terrain, pediment and coastal plain (National Authority for Remote Sensing and Sciences, 1997).

4.1.1. Mountainous terrain

It constitutes a part of the northern tip of Red Sea Hills in the northern Eastern Desert. It is built up of high-altitude belt of basement rocks trending parallel to the Gulf of Suez coast. It encounters several prominent high peaks such as Gebel Ghareb (1745 m), Gebel Abu Khashaba (1455 m), Gebel Samr El-Abd (1068 m) and Gebel Samr El-Qaa (893 m). This terrain is dissected by several deep and steep drainage lines, highly bifurcated, forming dendritic and reticulated patterns. Many of the main drainage lines are mostly controlled by faults and fractures.

4.1.2. Pediment

This unit comprises the low-lying land adjacent to the feet of the mountainous terrain. It has almost a plain surface gently sloping eastward, and it is covered by cobbles, gravels and debris of rocks forming the mountains. At the same time, there are small rocky hills scattered within this pediment plain. The drainage lines passing through the pediment are shallow, with wide bottom, highly bifurcated with several braided branches and alluvial fans. The flow of water in these drainage lines is essentially under the influence of gravity and general slope eastwardly to the Gulf of Suez.

4.1.3. Coastal plain

Ras Ghareb area has a relatively wide coastal plain in comparison to other areas along the Gulf of Suez and Red Sea. It has a flat peneplained surface covered by sands and gravels, with some low areas of sabkha and saline flats. The coastal plain is characterized by shallow wide drainage lines with braided branches ended by deltas at the outlets of the main wadis draining to the Gulf of Suez. These wadis include Wadi Abu Had; Wadi El-Darb; Wadi El-Khariem; Wadi Abu Khashaba and Wadi Um Yusr.

4.2. Terrain characteristics

4.2.1. Elevation zones map

A digital elevation model DEM is a raster representation of a continuous surface, usually referring to the surface of the Earth. The accuracy of this data is determined primarily by the resolution. The DEM produced by the SRTM was classified into zones. These zones can be changed according to the threshold needed for each study. The elevation zones for the area that were constructed in this study are shown in Fig. 2.

4.2.2. Slope map

The slope function calculates the maximum rate of change between each cell and its neighbors, for example, the steepest downhill descent for the cell (the maximum change in elevation over the distance between the cell and its eight neighbors). Every cell in the output raster has a slope value. The lower the slope value, the flatter the terrain and the higher the slope value, the steeper the terrain. The output slope raster can be calculated as percent of slope or degree of slope. Degree of slope is a value between 0 and 90. The slope function was run using the SRTM DEM for investigated area and the product was the slope map (Fig. 3). Such map reveals the steepness and gentleness of the terrain and had been classified into zones based on area different slope angles. This map is very important as one of the GIS layers for its contribution in the surface runoff.

5. Geology and structures

Ras Ghareb area is located within a highly tectonized structural zone, trending from Gebel El-Zeit ridge parallel to the western coast of the Gulf of Suez and extending further to the north (EGPC, 1996). According to Klitzsch and Linke (1983), the mountainous terrain in the western side of the study

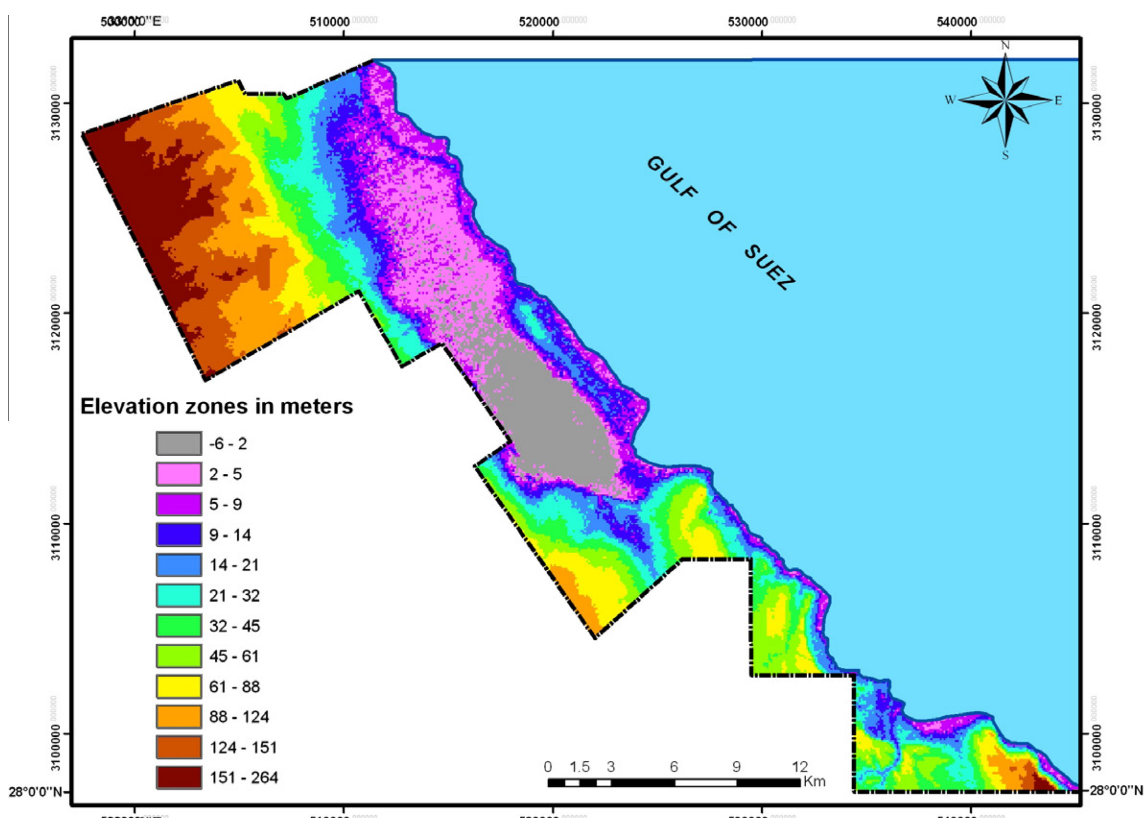

Figure 2 Elevation zones map of the study area derived from SRTM data.

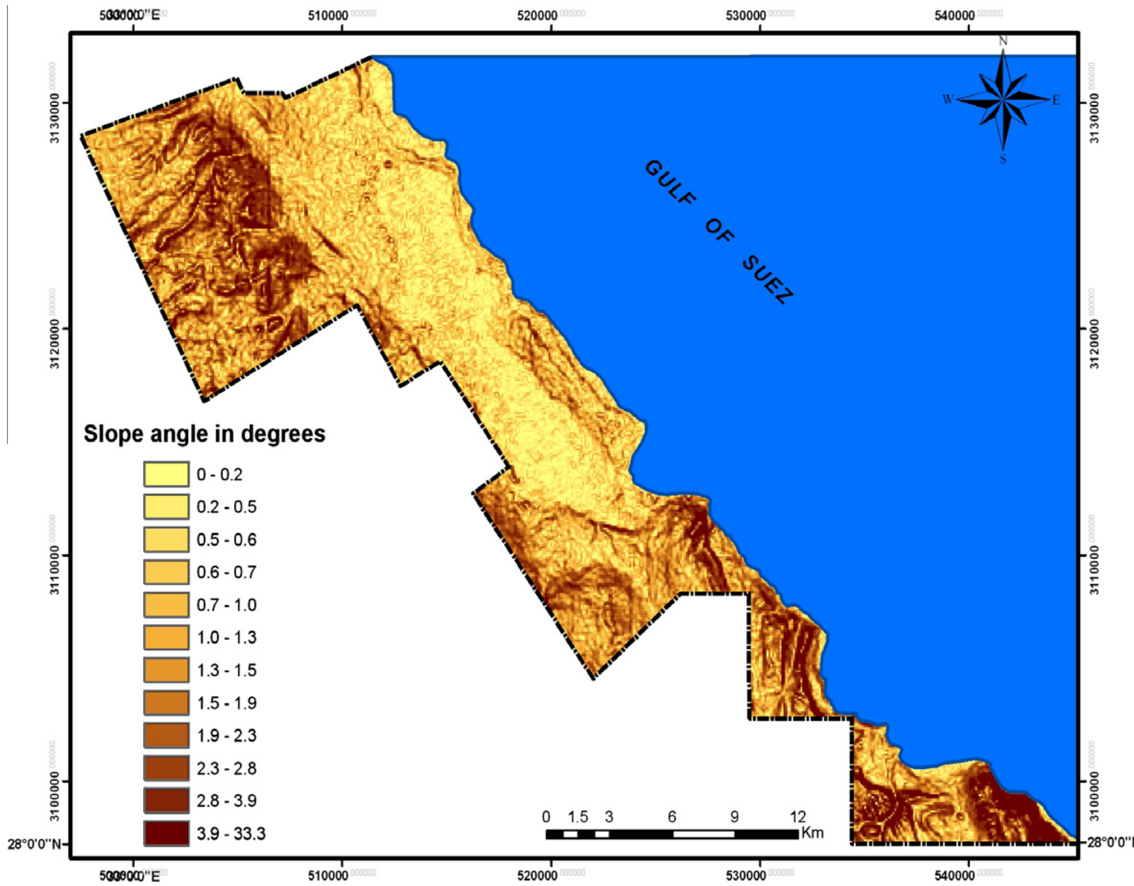

Figure 3 Slope angles map of the study area derived from SRTM data.

area is built up of more or less coherently high ridges trending parallel to the Gulf coast and interrupted by a number of detached masses and peaks. It is composed essentially of crystalline igneous and metamorphic basement rocks of Precambrian age, dominated by granitoid rocks and metavolcanics. Subordinate Upper Cretaceous sediments and Miocene evaporites are recorded in some detached outcrops. In some places, Pliocene deposits unconformably overlie Upper Cretaceous sediments. They are composed mainly of gravel, sand, sandstone and shale with limestone intercalations. On the other hand, at the feet of these mountains, the low-lying terrain of pediment is gently sloping eastwardly and it is covered by scattered outcrops of low-lying beds of Upper Cretaceous, Miocene and Pliocene sediments. Further to the east, the coastal belt exhibits a sedimentary sequence of Quaternary deposits, formed mainly of sands and gravels, sabkhas and saline flats, and alluvial deposits in the wadis crossing the area (Table 3, Fig. 4).

The boundary between the mountainous terrain and the low-lying terrain is distinct and runs generally along NNW–SSE trending normal faults. Furthermore, fractures are the dominant structural elements crossing various rock formations in the study area. The density, persistence, extensions and directions of these fractures are variable. However, the dominant fracture sets are those striking mainly in the NE–SW (N 30°–40° E), NNW–SSE (N 20°–30°W) and NNE–SSW (N 10°–20° E) directions.

Table 3 Lithostratigraphic sequence of rocks and sediments exposed in Ras Ghareb area.

Age	Lithology
Quaternary	Alluvial wadi deposits
	Sabkhas and saline flats
	Sand and gravels
Pliocene	Gravels, sands and sandstones, cemented with gypsum
Miocene	Evaporites, mainly gypsum, interbedded with shales and sands in the lower part
U. Cretaceous	Limestone with phosphatic layers
Precambrian	Granitoid rocks
	Metavolcanics

6. Hydrology and drainage basins

According to NARSS (1997) and Yehia et al. (2002), the surface drainage network in Ras Ghareb area forms some large drainage basins namely, from north to south: Wadi Abu Had; Wadi El-Darb; Wadi El-Khareim; Wadi Abu Khashaba and Wadi Um Yusr. All of these wadis are draining eastwardly to the Gulf of Suez (Fig. 5). This is in addition to the areas in between the outlets of these main wadis, which include some small short wadis, especially between Wadi Abu Had and Wadi El-Darb. There are two small round hills of 50–60 m

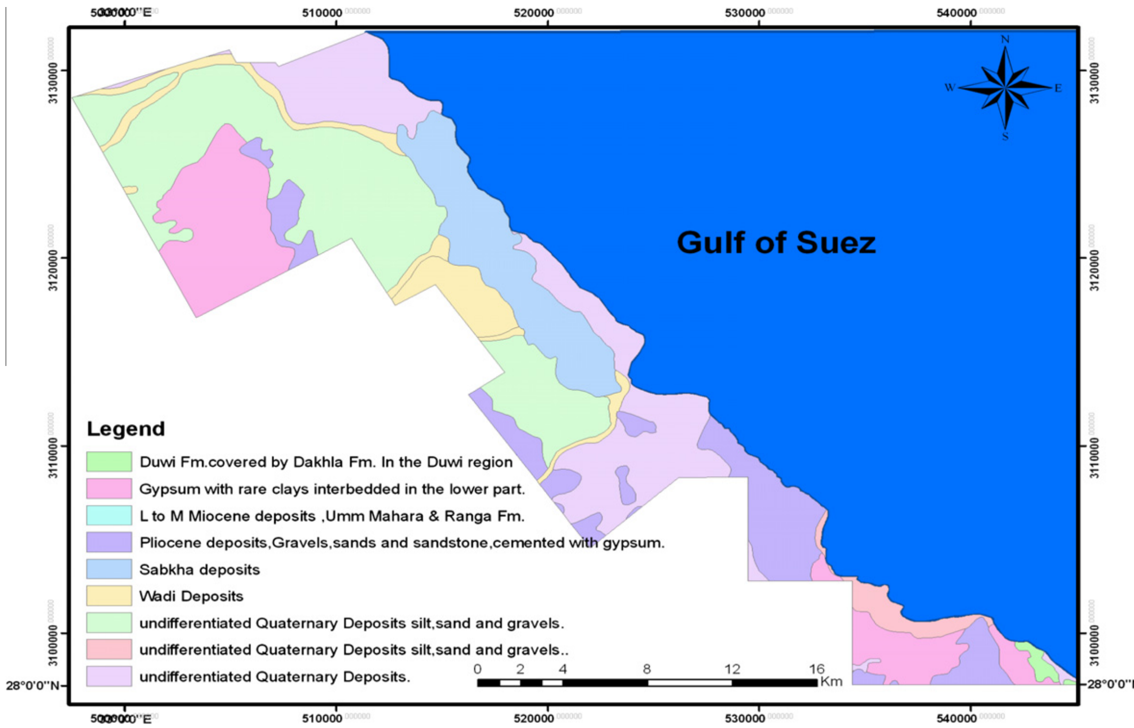

Figure 4 Lithology map of the study area (After EGPC/CONOCO-Coral, 1987).

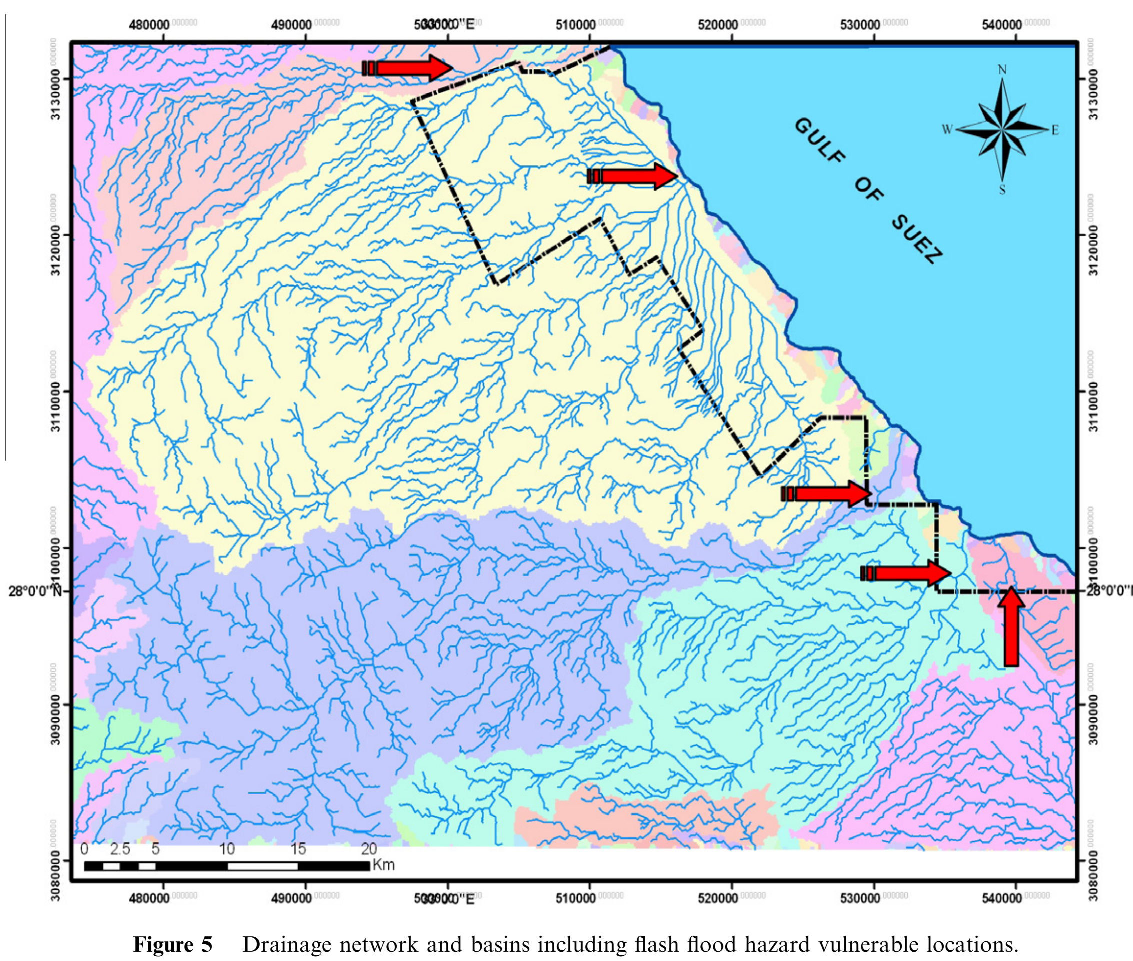

Figure 5 Drainage network and basins including flash flood hazard vulnerable locations.

elevations, draining by some short wadis flowing towards Ras Ghareb airport and the surrounding urban areas. The basins of these wadis are crossed by some main roads in the study area, such as the coastal Red Sea road. The drainage pattern in the study area is greatly affected by the prevailing trends of geological structures, where many parts of wadi lines are controlled by faults and fractures particularly of the ENE and NNW trends. Also, bends in some wadis are mostly found at the intersection of major fractures.

7. Environmental hazards

The ecosystems in Ras Ghareb area are highly productive, and generate an array of marine/coastal/terrestrial diversity of renewable resources. The area, with the colorful mountains in the western background, coastal beach and Gulf of Suez to the east, is considered to be of scenic beauty and high biodiversity. In 1938, the first oil discovery was made in Ras Ghareb area, followed by several others, and the area is considered the most prolific petroleum province in the Gulf of Suez. Over the last three decades, population increased due to the introduction of employment-generating activities for defense, mining, petroleum, fishing and fish farming and various public services. Currently, there is a threat of pollution resulting from these activities, particularly oil pollution, in addition to the impacts of flash floods that occur after occasional heavy rain storm causing disastrous hazards on roads and settlements.

7.1. Flash-flood hazards

In Ras Ghareb area, there are five main hydrographic basins, namely Wadi Abu Had, Wadi El-Darb, wadi El-Khreim, Wadi Abu Khashaba and Wadi Um Yusr. From the analysis and interpretation of Landsat ETM+ false-color composite images (with 30 m resolution), SRTM DEM data and topographic maps (scale 1:50,000), the drainage networks and boundaries of drainage basins have been accurately delineated. Measurements and statistical analysis of the extracted drainage pattern lead to the determination of geomorphometric parameters of the drainage in the study area (Table 4).

7.1.1. Wadi system and flash floods

Wadis, representing water courses after rainfall, are important arteries for fresh water in the study area. However, during periods of torrential rainfall, wadis can lead to flash floods and result in major damage. Hefny (1997) determined the risk factors of wadis, as having the characteristics of high, medium and low risk areas (Table 5). During floods, wadis also bring down sediments to low land and coastal areas. This can be damaging to the physical infrastructures and human settlements.

Table 5 Risk criteria of wadis and the characteristics of risk levels with respect to heavy flooding (After Hefny, 1997).

Risk Level	Risk factor			
	Water depth (cm)	Water velocity (m/s)	Max. diam of sediments (cm)	Volume of sediments (1000 m^3)
High	< 50	> 2.0	12.5	> 100
Medium	25–50	1.2–2.0	8.0–12.0	50–100
Low	< 25	< 1.2	< 8.0	< 50

Also, heavy sediment loads on coastal systems are harmful to coral reefs and other photosynthetic communities, such as coastal vegetation. These ecosystems stabilize shorelines and help prevent erosion. On the other hand, the nutrient input through wadis is beneficial for sea grasses and consequently to the production of fish associated with these ecosystems. Any future large scale management of wadi systems could have direct implications to human settlements and coastal systems. The flash floods of November 1996 caused some damages in the coastal road, particularly at the Km 30 along Zaafarana – Ras Ghareb Road (National Authority for Remote Sensing and Sciences, 1997).

It is worthy to notice that the main wadis, crossing the area eastwardly to the Gulf of Suez, have a direct influence on the roads, settlements and other human activities in the coastal zone. The hazard probability varies for the different basins according to their morphometric parameters, particularly the drainage frequency, density and bifurcation ratio. This is in addition to the basin area, slope, amount and velocity of runoff water flowing through the basin. The basins outlet delineated from the SRTM DEM revealed that three basins can affect the coastal road and the surrounding settlements located on the wadi mouth, whereas one of these basins is draining into the main water body of the area (wet sabkha). This means that the water ponds are essential for reducing the risk of flash flood hazard threatening its outlet (Fig. 5).

7.2. Surface water contaminations

The characteristic little to scarce rainfall resulted in the absence of perennial fresh water, except in some wadis during the occasional winter flood that reaches as far as the coast of the Gulf of Suez. This surface water, provided by runoff, is fresh and potable water, but limited in quantity. Occasional

Table 4 Some hydrographic characteristics and flash flood hazard assessment of the main drainage basins in Ras Ghareb Area (After NARSS, 1997).

S. No.	Drainage Basins Characteristics	Wadi Abu Had	Wadi El-Darb	Wadi El-Khreim	Wadi Abu Khashaba	Wadi Um Yusr
1	Area, km^2	1089.9	186.4	304	149.7	14.3
2	No. of drainage lines, N	5280	891	1553	448	66
3	Total length of drainage lines, km	3828.2	762.9	1290	385	134.3
4	Drainage density, K/km^2	4.9	4.78	5.11	3	4.6
5	Drainage frequency, N/km^2	3.98	3.8	4.2	3.25	3.88
6	Risk assessment	High	Moderate	Moderate	Moderate	Low

floods of the long wadis reach the coast, but wadi floods make their contribution in recharging the ground water aquifer system. In the sandy floors of the wadis, water can be reached at depths of around 10 m. However, most wells in the fringes of coastal flats are usually brackish, not suitable for human consumption, but some of it is drinkable by camels. Surface water contaminations in the study area of Ras Ghareb originate through two different processes namely;

(a) Oil pollution from petroleum leakage and waste discharge, and

(b) Salinization from highly saline sabkha and salt flats.

7.2.2. Oil pollution

Surface transport of petroleum wastes generally occurs when large amounts are discharged onto ground, especially in the existence of storm water runoff. Hydrocarbons move with surface runoff as they are lighter than water. Furthermore, surface water contamination in the study area is caused by surface leakage from the pipe lines linking the productive oil fields to Shukeir Station. This area is recorded to be highly polluted. This is because it is of lower elevation in comparison to its surroundings, where a higher pressure is created on the pipe line, making it more potential to leak.

7.2.3. Salinization of fresh water

When surface, and near surface, runoff water is accumulated in low areas covered with sabkha, rich in gypsum and halite, it is contaminated with salts and other pollutants. In these areas, surface water ponds are highly brackish to saline and not suitable for human use. In the study area, the largest exposed surface water lake of the sabkha is located near Shukeir Oilfield. Smaller sabkha lakes exist in different parts on both sides of the coastal road. Some parts of the sabkha include salt concentration ponds, such as those located between Shukeir and Um Yusr Oilfields.

Comparing Landsat-TM dated 1984 and ETM+ dated 2000 images revealed that the area of the sabkha has expanded in the past 16 years from 0.79 km^2 to 0.93 km^2 which means an increase in its area by 0.14 km^2 (Fig. 6). This increase took place mainly in the area to the north of Um Yusr Oilfield. This is probably related to the discharge of produced water from the oil operation into two large evaporation ponds and finally dissipated to the sabkha. Stretches of produced water with obvious oil contamination were also detected in wide areas of sabkha near Um Yusr Oilfield.

7.3. Groundwater contamination

The geomorphological parameters of the hydrographic basins and the hydromorphometric analysis carried out in the study area indicated that the basins are of high flooding probability and low groundwater potential. This means that the effect of surface or near surface runoff is higher than that of groundwater in terms of point contamination from surface oil leakage in the area. In other words, the pollutant transport is following a horizontal surface, or near surface, runoff pattern rather than

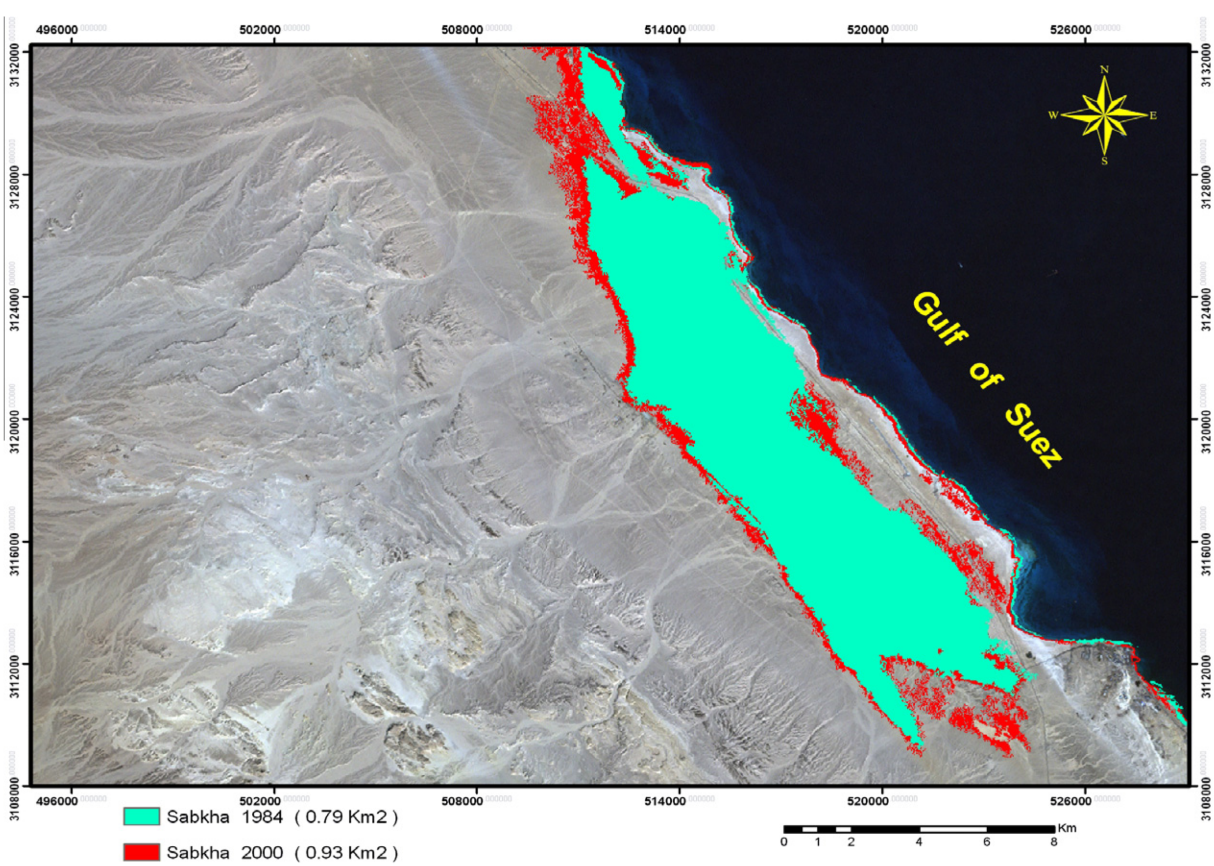

Figure 6 Change in water body including sabkha boundary in the study area through the years 1984 and 2000.

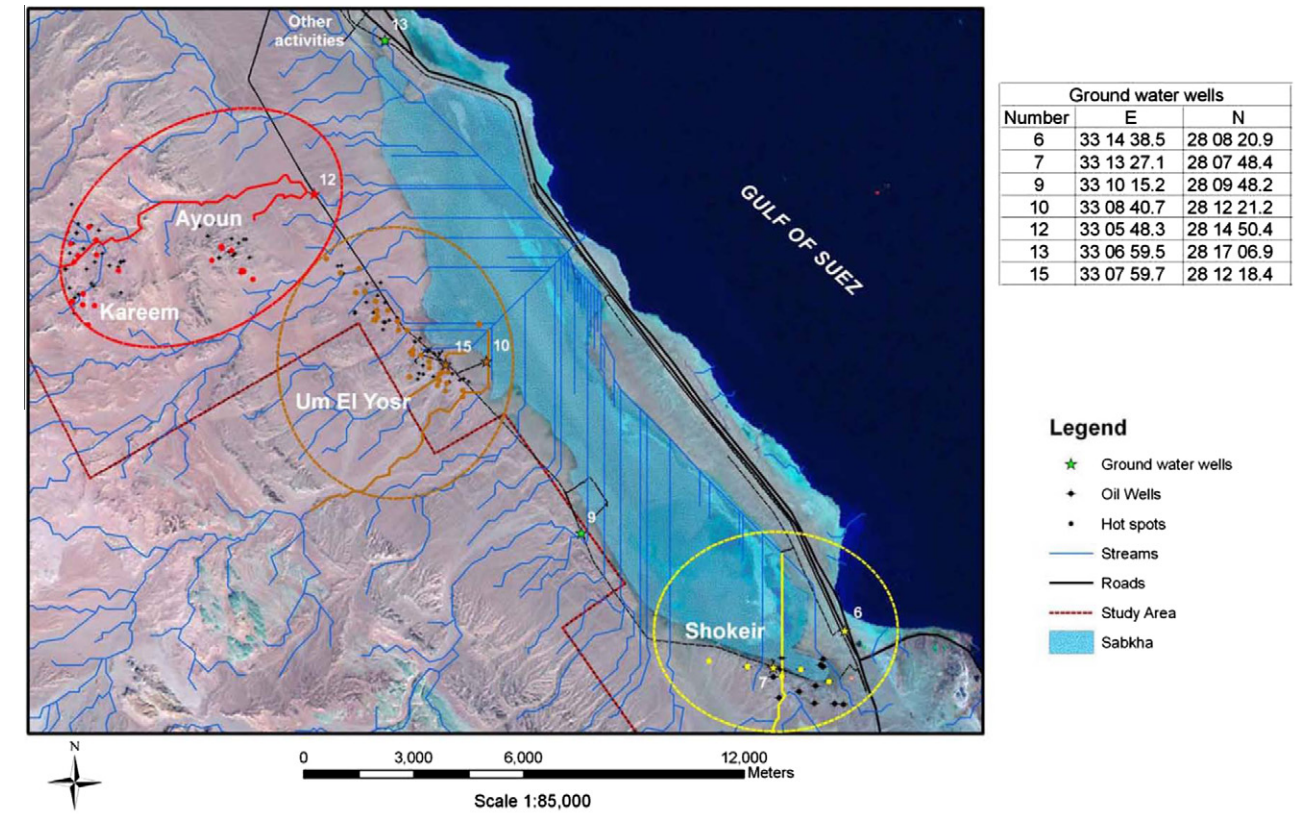

Figure 7 Location of ground water monitoring wells related to pollution hotspots.

a vertical leaking pattern. Accordingly, the areas where maximum effect on water quality, as a result of pollutants spills in the study area, are the low elevation areas within the drainage network. This particularly applies to the points where drainage lines intersect with sabkha.

Seven monitoring wells were localized and identified, using GPS, at this intersection for collecting groundwater samples for laboratory analysis (Fig. 7). This aims to reflect the fate of spills resulting from the activities at the oil fields in the area. Crude oil is generally composed of a wide range of hydrocarbons

Table 6 Groundwater analyses results.

Parameters	Units	Well numbers							Intervention values (Dutch standards)
		10	12	15	6	7	9	13	
Water temp.	°C	22	22	22	22	22	22	22	–
pH	–	7.2	7.4	7.5	7.8	7.6	7.8	7.8	–
Electrical conductivity	μm ho/cm	62,000	77,000	43,000	50,000	18,000	31,000	46,000	–
BTEX (Total)	μg/l	ND	0.041	0.092	ND	0.049	ND	ND	
Benzene	μg/l								30
Toluene	μg/l								1000
Ethyle Benz	μg/l								150
Xylene	μg/l								70
T. Petr HC hydrocarbons	μg/l	173	114	169	10	24	126	163	Site specific
Iron	mg/l	5.8	6.1	6.0	5.5	6.2	6.1	5.6	
Manganese	mg/l	ND	ND	ND	ND	ND	ND	ND	
Copper	mg/l	0.071	0.069	0.08	0.076	0.082	0.077	0.074	0.075
Zinc	mg/l	0.198	0.182	0.211	0.175	0.201	0.177	0.164	0.8
Lead	mg/l	0.92	1.32	1.45	1.53	1.11	1.08	1.16	0.075
Cadmium	mg/l	0.085	0.093	0.09	0.089	0.078	0.082	0.091	0.006
Chromium	mg/l	0.018	0.022	0.023	ND	0.016	0.02	ND	0.03
Selenium	mg/l	ND	ND	ND	ND	ND	ND	ND	0.16
Arsenic	mg/l	ND	ND	ND	ND	ND	ND	ND	0.06
Cyanide	mg/l	ND	ND	ND	ND	ND	ND	ND	1.5
Mercury	μg/l	ND	ND	ND	ND	ND	ND	ND	0.3

and a small amount of impurities, in addition to different types of heavy metals including arsenic, cadmium, mercury and nickel (Zein El-Din and Shaltout, 1982). Moreover, the produced water during oil exploration and production activities could generally be a source of brine, petroleum hydrocarbons, natural radioactivity and heavy metals. Leaks, spills and releases of this water may contaminate both soil and groundwater. Heavy metals could also result from additives used in petroleum activities, disposal of drilling mud and other wastes.

The results of analysis of the collected groundwater samples, and the intervention values (Dutch threshold standards) indicating the necessity for remedial action, are given in (Table 6) and briefly discussed in the following.

7.3.1. Total petroleum hydrocarbons (TPH) and benzene, toluene, ethyl benzene and xylene (BTEX)

The TPH were measured to determine the concentration of petroleum in the soil, where the results indicated the existence of low levels of TPH in the groundwater. Also, the total measured BTEX levels were found lower than the intervention values of any of its individual components.

7.3.2. Heavy metals

Zinc, chromium, selenium, arsenic, cyanide and mercury were found below the intervention values. Copper levels were found around the intervention values, whereas lead and cadmium are above the intervention values.

In general, the results of the groundwater analysis were found consistent throughout the sampled locations, where values exceed the intervention levels for lead and cadmium in all samples. However, the highest levels of cadmium were found near Kareem and Al-Ayun Oilfields. The analysis also showed that the highest levels of TPH and BTEX were detected at wells number 10 and 15, respectively, which are downstream Um Yusr Station. It is worthy to mention here that subsurface transport of petroleum wastes could occur above the water table or through the geologic formation, especially when abandoned oil wells are improperly plugged. In this case, hydrocarbons, salt and heavy metals may flow into formation that contain fresh groundwater aquifers.

8. Conclusion

This study applied different remotely sensed data, both optical (Landsat TM and ETM+) and radar (SRTM), with the field investigations and measurements in a GIS environment. Space borne and ground data had been acquired and analyzed in an integrated approach. Surface water regime was mapped from SRTM data, changes in water bodies and sabkha areas were detected from the multi-temporal Landsat images. Field investigations located the point contaminated locations. Spatial distributions of such point contamination in the surface water régime were concluded. Groundwater testing wells were sited using information about the surface drainage network and the point contamination spatial distributions.

In conclusion, the investigations proved that there has been a detectable negative impact on the groundwater quality. It is difficult to relate the contribution of each activity in the area to this impact. However, it is concluded that the pollutants were transported, from their potential sources of production and other activities in the area. This flow will happen through surface runoff and near surface waters towards the lower elevation areas and following the slope of the terrain surface and dip of near surface aquifers. The outlet for all these water flows will be the low land sabkha body in the eastern part of the area. Consequently, the monitoring wells suggested by this research located at definite locations will be the indicator for the pollution status in different parts (oilfields) of the area. Fig. 7 indicates location of ground water monitoring wells and their relation to identified hotspots as well as their relation to oil production and other activities. Currently, groundwater is of no use in the area as it is of high salinity. Surface water in the main water pond appears to be healthy. An exception is the northern parts of the sabkha. Some other locations that include small ponds are located in the upstream operations in wells and block stations. It is expected that if the sources of pollution in the area are cleaned and discontinued, the quality of both surface and groundwater will improve with time. The applied methodology and techniques proved the feasibility of using different remotely sensed data, field investigations and measurements in a GIS environment for pollution monitoring and environmental management.

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